Automatic Generation of Milling Toolpaths with Tool Engagement Control for Complex Part Geometry

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    - CNC milling issues
    - Tool Engagement Angle
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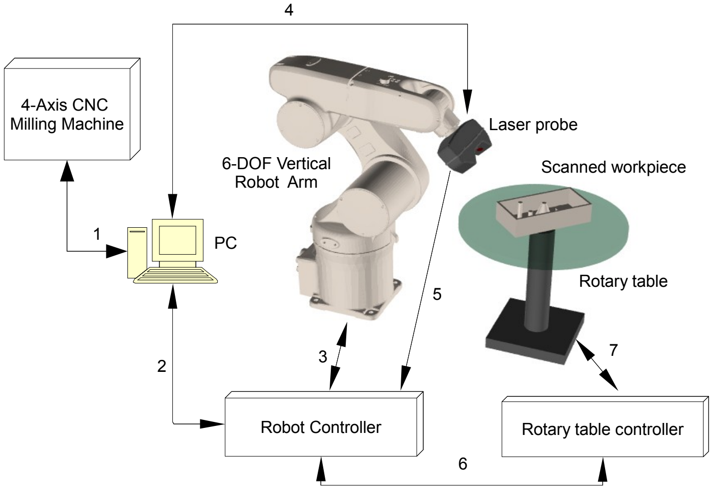
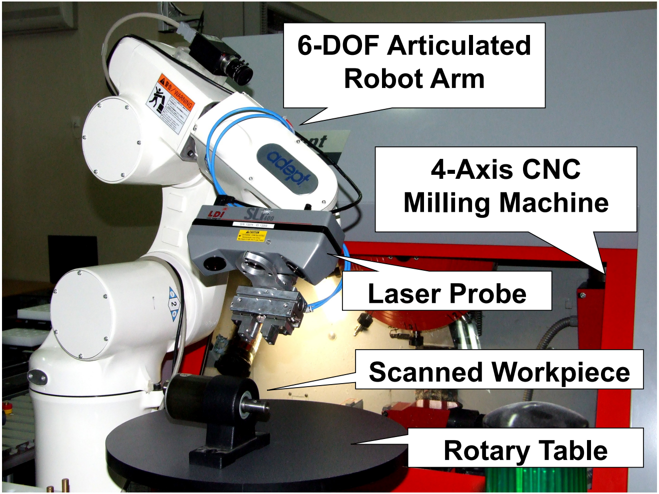
3. Proposed algorithm and experimental results
    - Milling parts for algorithm evaluation
    - Traditional toolpaths
    - Proposed algorithm
    - Results
4. Conclusions

3D Laser Scanning System Overview



3D Laser Scanning System Overview



Main issues for CNC milling

CNC milling

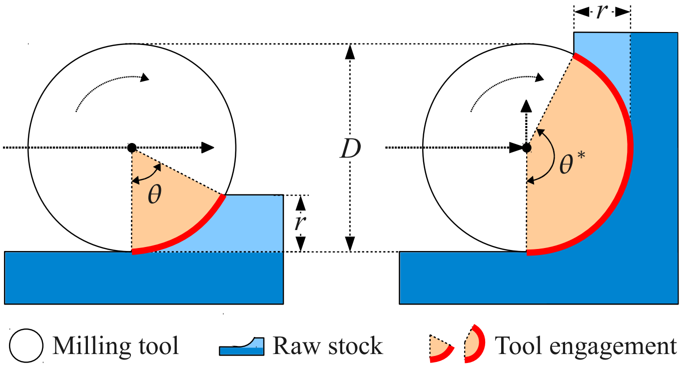
- Automatic CNC toolpath generation
- Milling parts with complex geometry
- Minimizing CNC milling time *without* overheating the cutting tool

Proposed solution

- Depth map modelling of design part and raw stock
- Natural representation for 2.5D milling operation
- Can be extended to 4-axis milling

Tool Engagement Angle

- The amount of sweep subentended by each cutting edge as it engages and leaves the stock
- Proportional to the cutting forces
- It is known to increase at internal corners in the toolpath

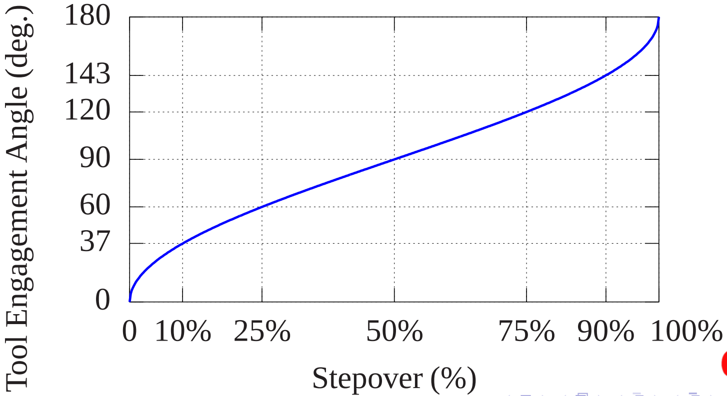


Tool Engagement Angle ⟷ Stepover

On straight line toolpaths, TEA (θ) is proportional to stepover (s):

$$s = \frac{1+\sin(\theta - 90^\circ)}{2}, \qquad 0 \le \theta \le 180^\circ \tag{1}$$

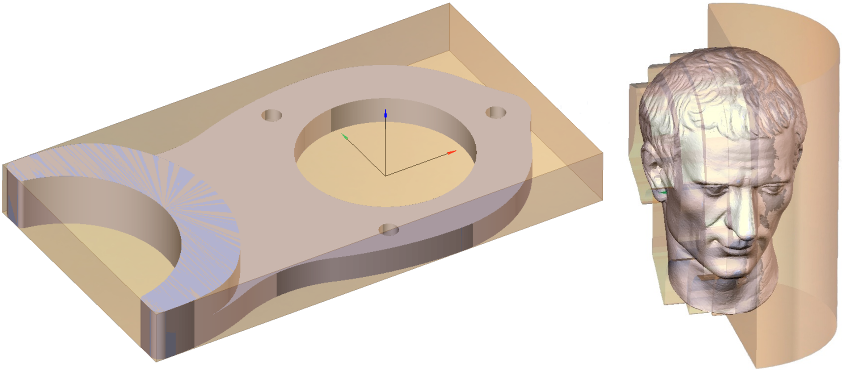
$$\theta = 90^\circ + \arcsin(2s-1), \qquad 0 \le s \le 1 \tag{2}$$



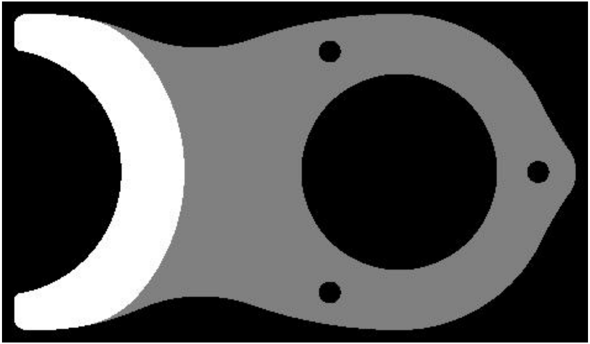
Related work

- Coleman (2006) explains the problem well, with intuitive examples
- Stori and Wright (2000): modified offset toolpath for convex contours
- Bieterman (2001) replaced contour-parallel toolpaths with a smooth spiral, nearly circular at pocket center, and slowly morphing into the part shape as it gets closer to the part
- Ibaraki et al. (2004) removed the convexity requirement from Story and Wright's approach
- Wang et al. (2005) defined a set of quantifiable metrics which can be obtained by pixel simulation
- Uddin et al. (2006) applied the Ibaraki's approach for improving tolerance on the finishing part by offsetting it nonuniformly, so that the finishing step is done at constant tool engagement
- Rauch et al. (2009): constraints-based trochoidal toolpaths

Milling parts for algorithm evaluation

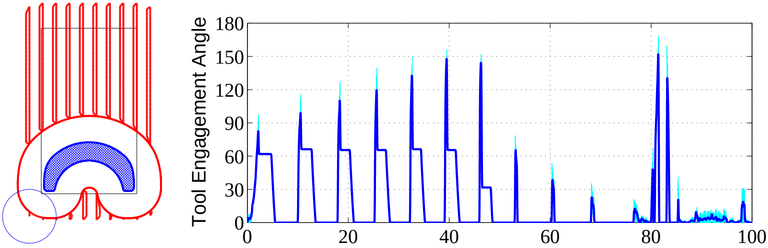


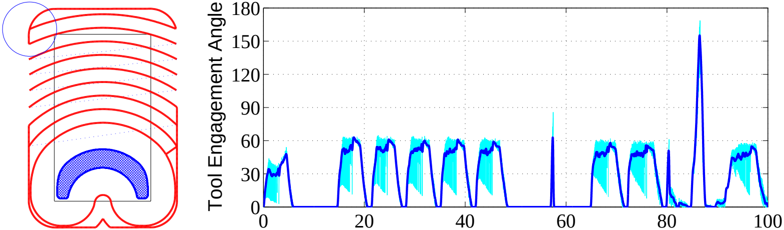
Milling parts – depth map representation



Traditional toolpaths

Direction-parallel toolpaths

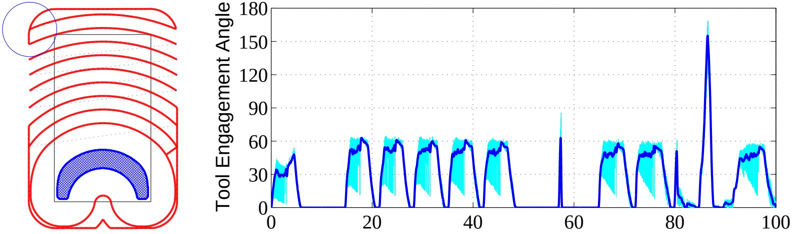


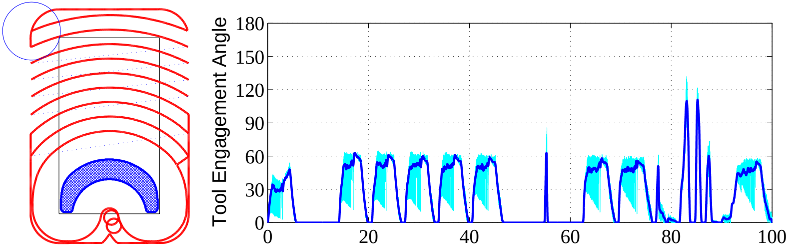


Contour-parallel toolpaths

Trochoidal Step (SprutCam v7)

Contour-parallel toolpaths

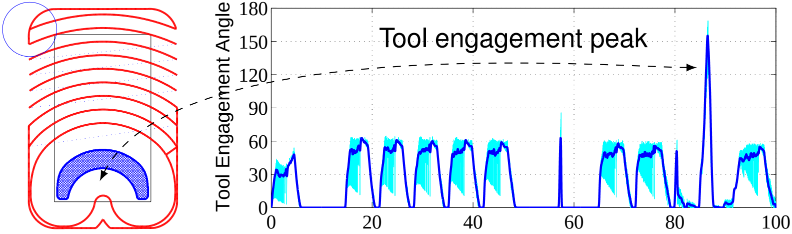


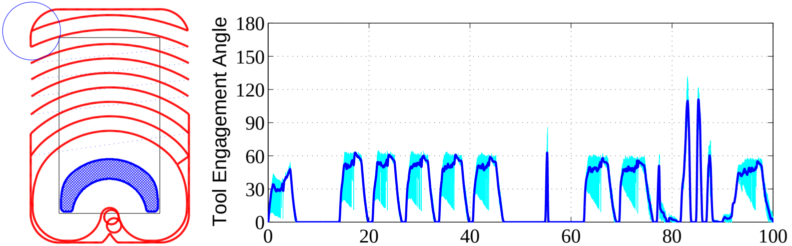


Contour-parallel toolpaths with trochoidal step

Trochoidal Step (SprutCam v7)

Contour-parallel toolpaths





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Trochoidal Step (SprutCam v7)

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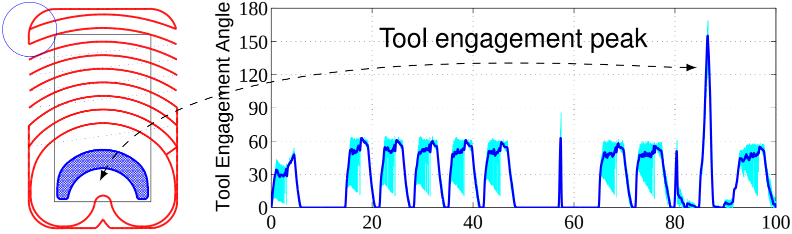
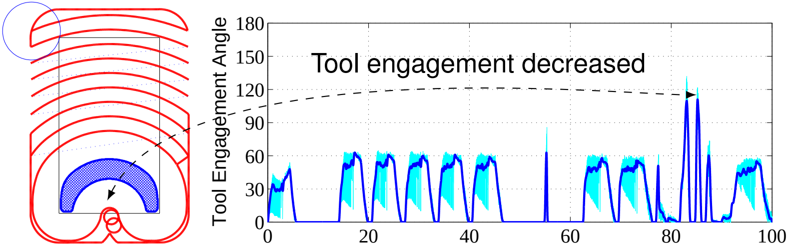
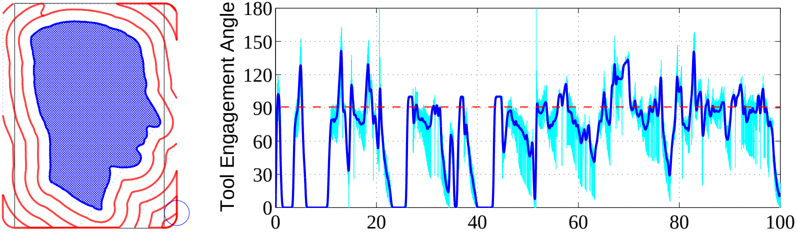


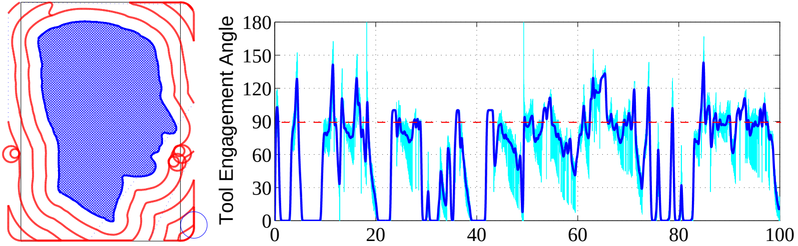


Contour-parallel toolpaths with trochoidal step

Trochoidal Step for Complex Geometry (SprutCam v7)

Contour-parallel toolpaths

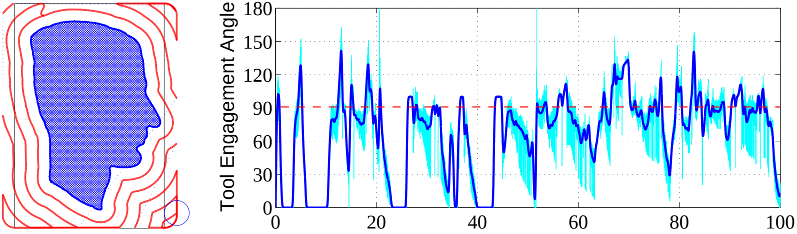




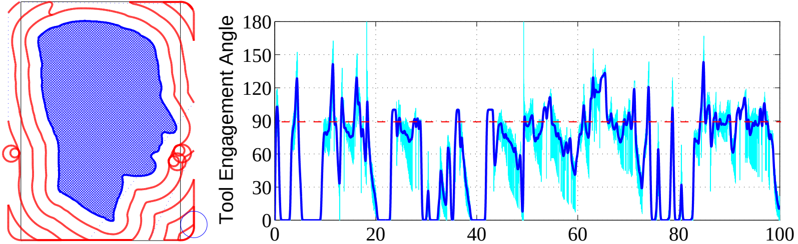
Contour-parallel toolpaths with trochoidal step

Trochoidal Step for Complex Geometry (SprutCam v7)

Contour-parallel toolpaths



Tool engagement peaks are still present!



Contour-parallel toolpaths with trochoidal step

Proposed algorithm

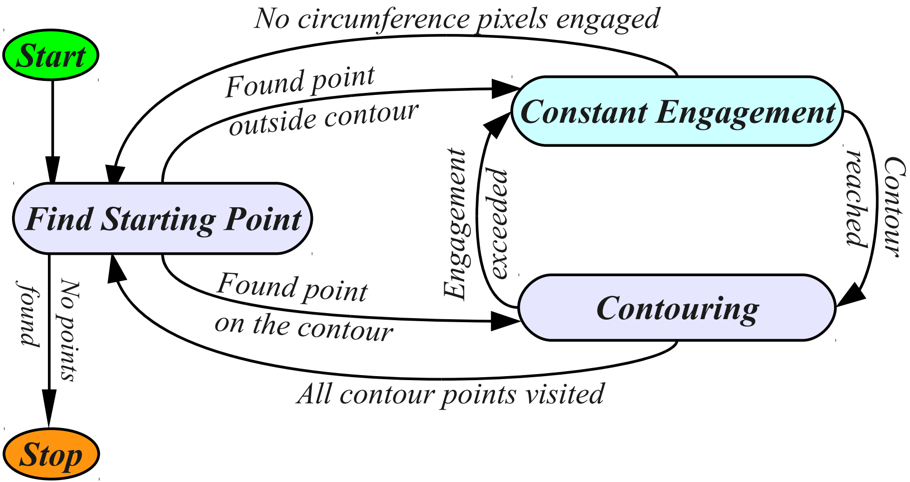
Input

- Tool diameter
- Prescribed tool engagement angle
- Binary image representing the design part (2D section)
- Binary image representing the raw stock (2D section)
- The 2D sections can be obtained by thresholding a 3D depth map

Output

- 2D milling toolpaths consisting of small linear segments
- Raw stock shape after the generated milling operation

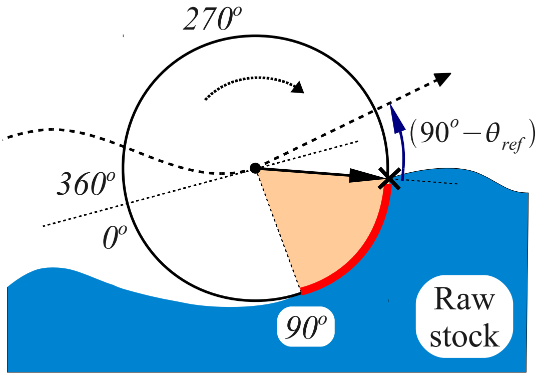
Proposed algorithm



Constant Engagement Milling

Main section of the algorithm

- Milling a raw stock with arbitrary shape
- The only constraint is the tool engagement angle
- The raw stock shape is updated at every step



○ Milling cutter

× Intersection point

◔ Engagement

Previous trajectory

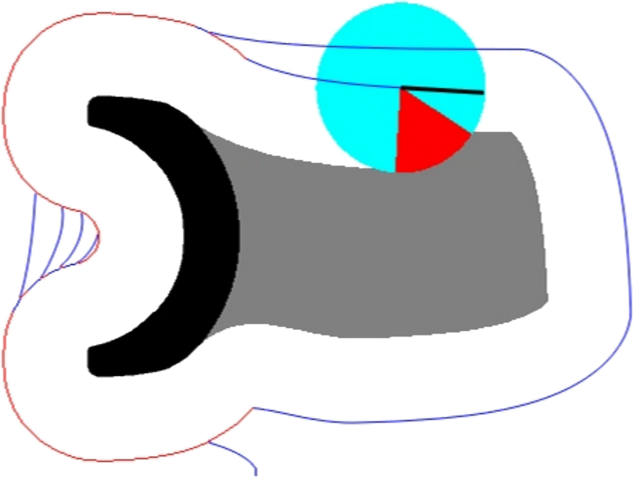
Advancing direction

Advancing direction for 90° TEA: α_{90}^{climb}

Previous advancing direction: α_p

Constant Engagement Milling

Example: toolpath with constant engagement for arbitrary raw stock shape



Contour Milling

Contour Milling

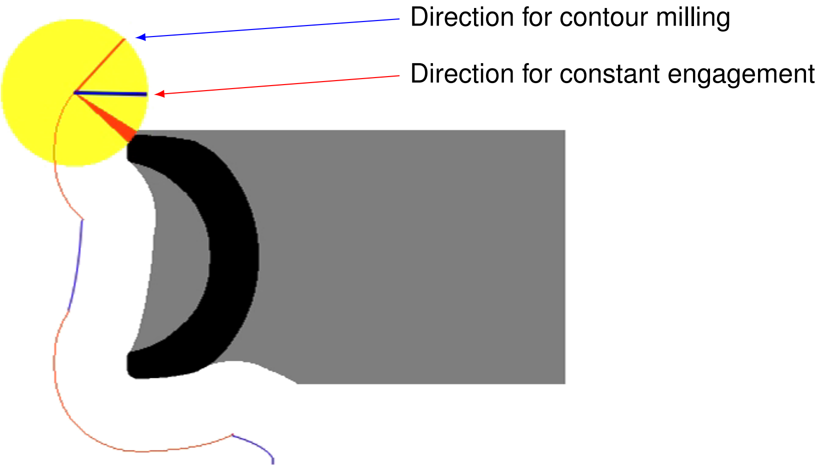
- Tool moves along the *offset contour*
- Tool is always tangent to the design path
- Usually, tool engagement angle is much smaller than the prescribed value

Stop conditions

- When TEA exceeds the prescribed value with more than a small threshold, the algorithm switches to Constant Engagement mode
- When all contour points are visited, the algorithm will search for a new starting point

Contour Milling

Example: Contour milling for the test part

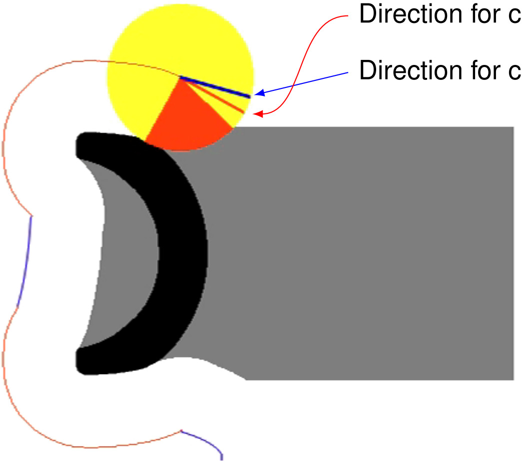


Direction for contour milling

Direction for constant engagement

Contour Milling

Tool engagement angle exceeded the prescribed value

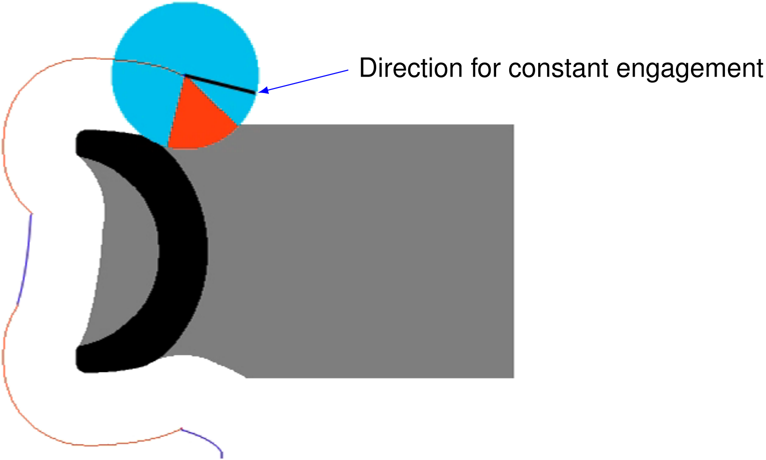


Direction for contour milling

Direction for constant engagement

Contour Milling

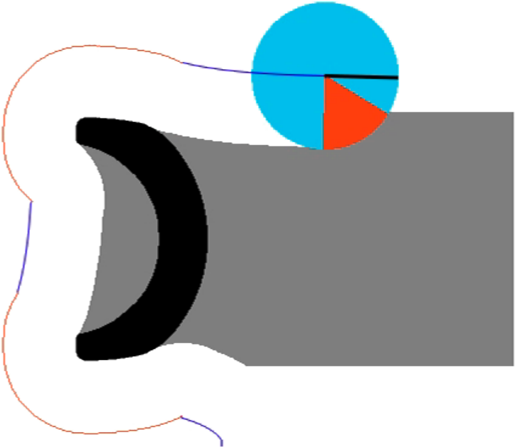
The algorithm switched to constant engagement milling



Direction for constant engagement

Contour Milling

The algorithm switched to constant engagement milling



Finding Starting Point

The first possibility is chosen from the following:

1. Continue a contouring operation, from the point where the algorithm switched from *Contouring* to *Constant Engagement*
2. Enter the raw stock horizontally, from lateral
3. Plunge the cutter into raw stock

Input

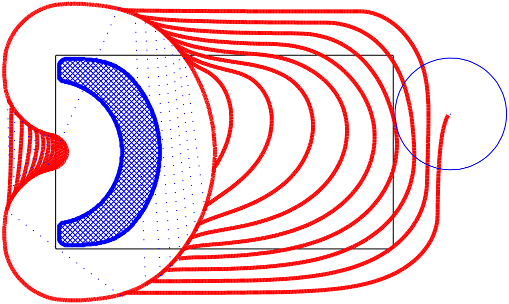
- Current cutter position: (x_0, y_0)
- Current raw stock and part shapes (2D images)

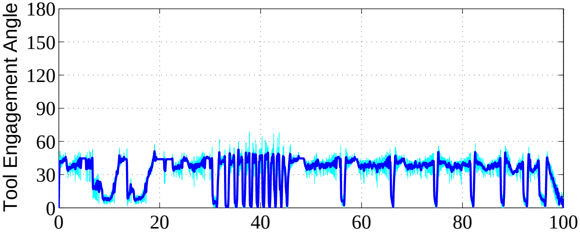
Output

- Starting point for next milling operation: (x, y)
- Milling trajectory for moving the cutter to (x, y):
  - Cutter retraction moves or tangent / plunge entry toolpaths

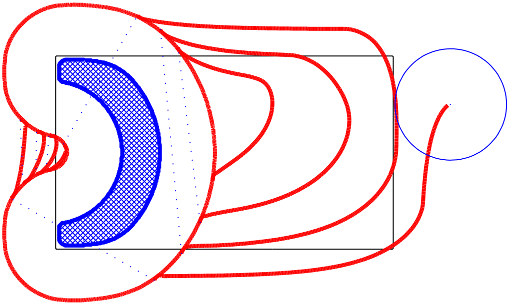
Example movie

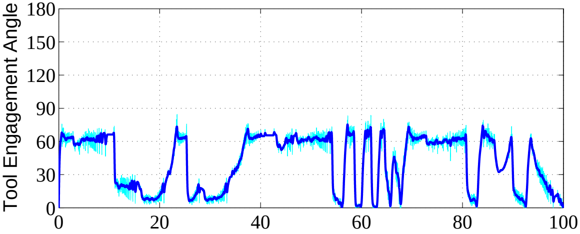
Results – 37° engagement



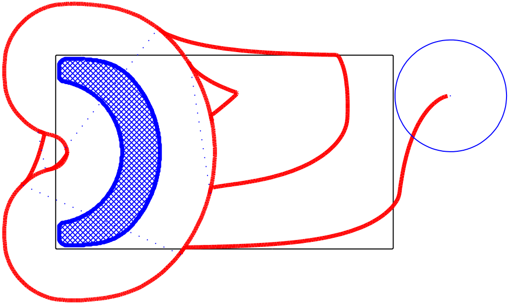


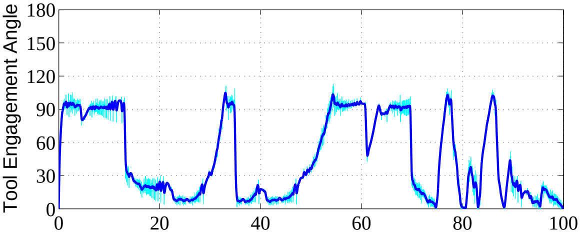
Results – 60° engagement



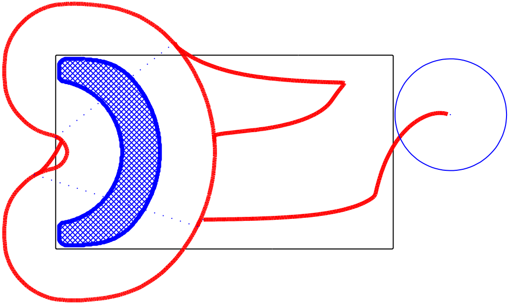


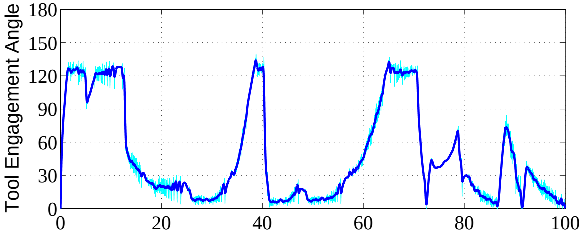
Results – 90° engagement



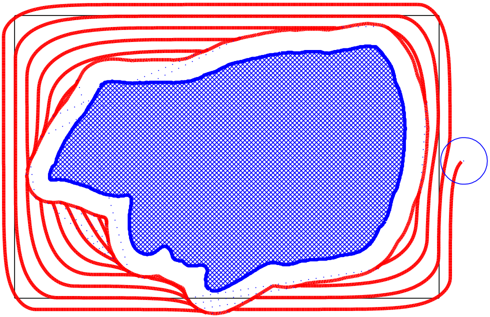


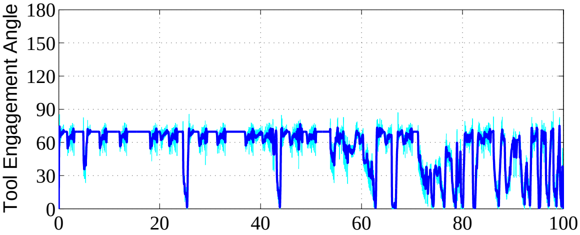
Results – 120° engagement



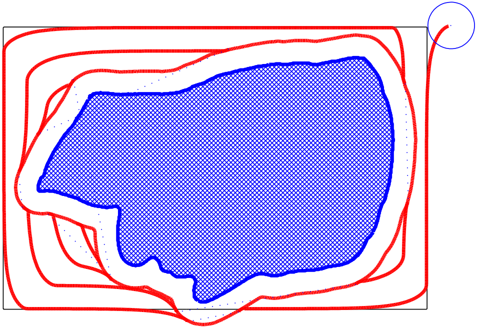


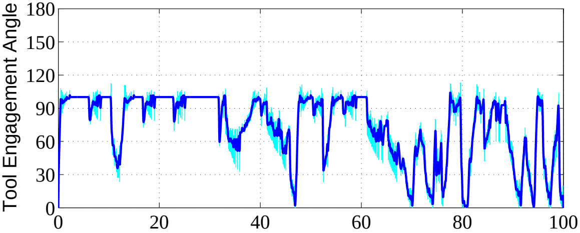
Results – 60° engagement





Results – 90° engagement





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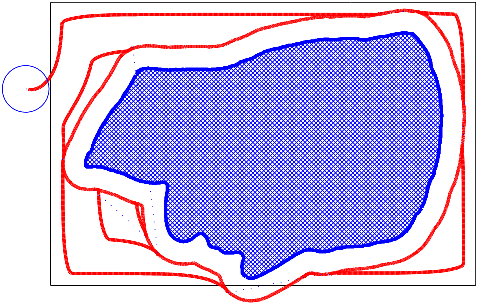
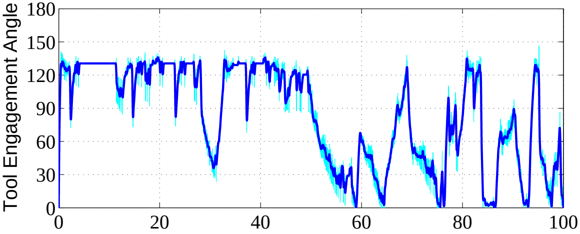
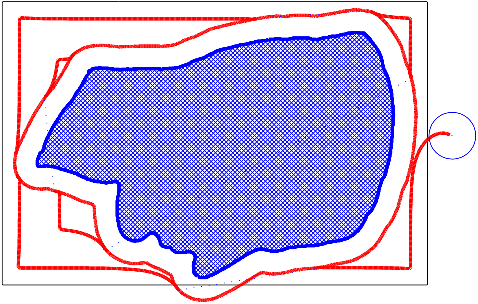
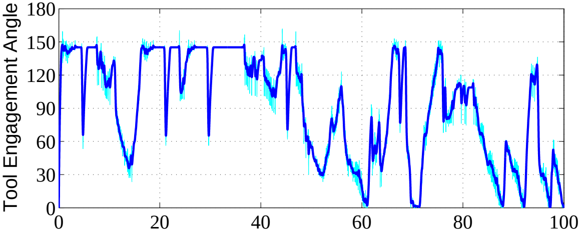




Results – 135° engagement

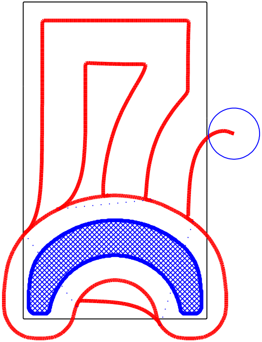


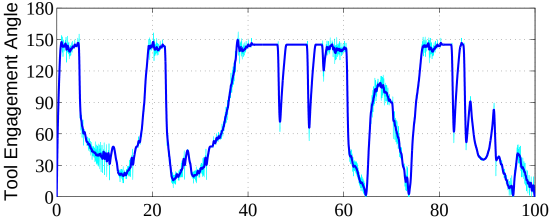


Sharp corners

Sharp corners

- The generated toolpath may contain *external* corners
- These corners do not cause an increase in the tool engagement
- However, they are not good for machine dynamics
- Corners are smoothed by the machine controller, with G64





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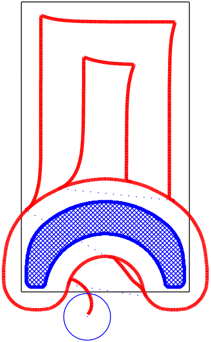

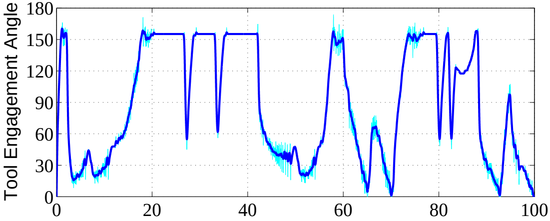

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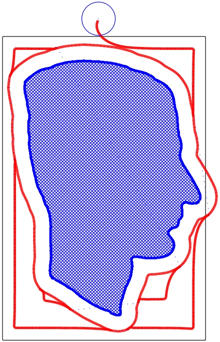
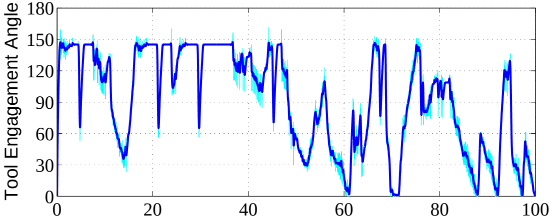
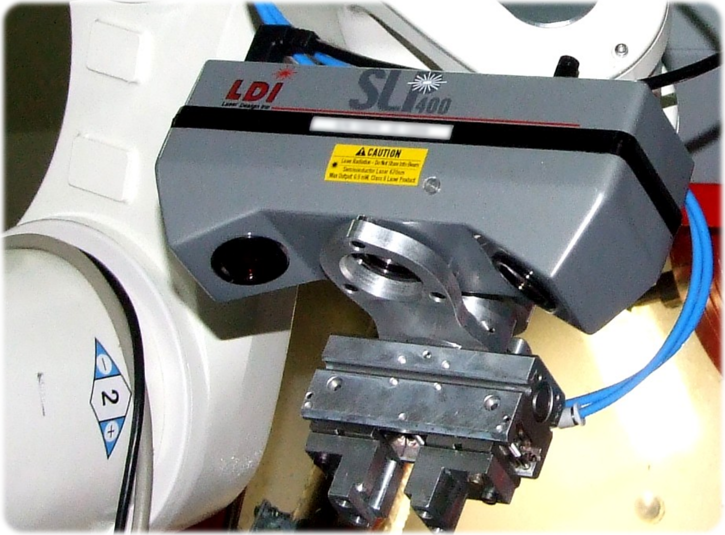




Results



Results

Conclusions

- 2D toolpath generation with tool engagement control
    - Prescribed reference value for engagement angle
    - Maximum allowed overshoot (default: 20°)
- Toolpath consists of small linear segments
- Suitable for arbitrarily complex *part* and *raw stock* geometry
- Raw stock geometry can be digitized with 3D scanning
- Reduces lubrication requirements and increases tool life
- Higher feed rates can be used, compared to traditional toolpaths
- Best results are obtained using this method for roughing, combined with the method from (Uddin et al., 2006) for finishing
- The algorithm is used for milling complex 3D surfaces on milling machines with 3 or 4 axes